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Optimal utilisation of heat demand in district heating system—A case study

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ABSTRACT

Global warming is one of the most important issues to handle in the energy sector, due to the high CO_2 emissions from fossil fuel based power plants. The district heating sector can play a significant role in reducing the emissions. This, however, depends on how efficiently current and future heat demands are used as a heat sink.

This paper presents the results of a model study of a district heating system (DHS). As a case study, a local DHS in a town in Sweden has been modelled using a linear programming method. The electricity generation system in northern Europe is also modelled in simplified way to serve as an input. The purpose of this study and modelling in this way is to answer the questions concerning the choice of technology solutions and fuels from an economic and an environmental point of view where the focus is on the local DHS. The main objective is to study the impact of different levels of biomass prices and emission allowances on the choice of fuels and production technologies (no other taxes, fees or any kind of subsidy are considered). The results show that low biomass prices along with high emission costs promote investment in biomass-based cogeneration. However, this would mean that the market price of existing renewable incentives and CO_2 cost must be higher than the current level. Furthermore, biomass as it is used now in traditional CHP system is not system optimal. In an integrated system, plants with high electrical efficiency provide better economy and lower emissions of global CO_2 than solutions based on traditional biomass CHP. The need for a system solution where the heat demand is used efficiently is seen in facilities with high electrical efficiency.

Contents

1. Introduction

Global warming has put the focus on the issue of CO_2 and that CO_2 emissions must be reduced. Most emissions of CO_2 come from power generation and transport sectors. According to an agreement signed by EU heads of state and government, a number of measures have to be taken to address energy supply security and climate change issues. One of the measures proposed by the EU is to cut green house gas emissions by 20% compared with 1990 levels [1]. Each member state has to reduce its emissions by a certain percentage compared to 2005 [1]. In Sweden, the target is a 17% reduction of CO_2 emissions. Countries that have recently

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become members are permitted to have an increase in emissions in order to secure their economic growth. In addition to the reduction of greenhouse gases, a target has been set that 20% of final energy consumption in 2020 must come from renewable energy sources [2]. The objective also includes a 10% share of renewable fuel for vehicles. In addition, primary energy use must be 20% lower by 2020 compared with projected level [3].

One of the major policy measures for reducing CO_2 is allowances for emissions. These are limited and connected to a cost and there is a trade mechanism for them. By lowering the amount of allowances, the cost will rise and provide incentives for investments in new CO_2-clean technologies and programmes for reduced consumption of electricity. In Europe, a scheme for emission allowance trading was established by the directive from 2003 [4]. The European emission trading scheme (EU ETS) started in January 2005 and covers many installations in the industrial and energy sectors. The first phase of the EU ETS ran from 2005–2007 and the second phase of the trading scheme that started in 2008 was completed in 2012. The scheme is now in its third period and this will run from 2013 to 2020.

It is a well-known fact that a large proportion of the CO_2 emissions come from electricity production based on fossil fuels. To reduce emissions, it is thus important to reduce the use of electricity as much as possible. Since the world is highly dependent on electricity, it is important to find solutions that reduce emissions while maintaining cost effective production. Different fuels and technologies will contribute differently to emissions of CO_2 depending on electrical efficiency and type of energy source. Natural gas and the combined cycle technology give relatively low emissions while coal condensing steam turbines produce relatively high emissions. The use of biomass as an energy source gives low or no emissions of CO_2. A problem with biomass, however, is that it does not provide the same high electrical efficiency as, for example, conventional fuels.

With this in mind, district heating can play an important role to reach some of the energy and environmental targets. A district heating scheme (DHS) is a system where the product (hot water) is generated centrally. The hot water is then distributed through pipeline to different types of customers that are connected to the network. One of the main benefits of DHS is that it enables the use of combined heat and power production (CHP) and makes the overall system efficient. It allows also the use of biomass and other sources of heat such as industrial waste heat. An overview of district energy system from technical, economic and environmental perspectives is given in [5].

Scandinavia is one of the regions of the world where district heating (DH) has long been established. All major cities and towns in Denmark, Sweden and Finland use DH for domestic heating and its share of the heat market in these countries is significantly high. This is not, however, the case in Norway, which has a rather low share even though the climate conditions are similar to those of its neighbouring Nordic countries. The main reason for this is an abundance of hydropower, which directly or indirectly encourages the use of electricity in the heating sector. Nonetheless, district heating is increasing steadily and the growth potential is higher in Norway than in the rest of Scandinavia.

Although a DHS enables the use of CHP, the degree of utilisation of CHP differs from country to country. In the case of Sweden, the development of CHP was different from some of the Nordic countries. When DH was established in the 1960s, a few CHP plants were also introduced. Originally, various fossil fuels like oil and coal were used, but after the oil crises of the 1970s biomass began to be used based on logging residues from forestry industries. During the 1980s the development of nuclear power in Sweden was completed and this has led to a surplus of electricity and hence low electricity prices. No effort was therefore made to promote electricity generation from CHP plants. On the other hand, there was a continuous expansion of DH based on hot water production from biomass to reduce oil dependency for space heating. This has led to a substantial increase in the share of biomass in the Swedish district heating production. For instance, the share of biomass in the total energy input for district heat production was about 40% in 2011 [6]. Another factor that contributed to increased use of biomass in the last years is the deployment of biomass based CHP. In this case, the introduction of the renewable incentive (see section 2) has played a vital role.

Today, the Swedish DHS has a significant share in the final energy and the system has one of the most diversified fuel mixes in the world. However, district heating seems to have reached its peak in Sweden and the possibility of further expansion is limited. Therefore, the focus is now how to reach other areas where the share is low and to find other application for district heating. Expansion in heat spares areas, energy carrier-switching in industries and poly-generation systems are measures that could lead to efficient DHS. Different studies which highlight these themes can be found in [7–11]. Moreover, there is also a concern regarding low energy buildings which might create difficult condition for the competitiveness of district heating. According to the directive on the energy performance of buildings, all new buildings are expected to have minimum energy requirement [12]. There is therefore a need to effectively utilise existing and future heat demand.

Although district heating is well established in Sweden, the existing district heating demand is still not utilised optimally. This is particularly true regarding CHP. The Swedish DHS still lags far behind leading countries like Denmark and Finland when it comes to the deployment of CHP. For instance, as much as 80% of the district heat supply in Denmark comes from CHP plants [13] and the share of CHP in the total power balance is high [14]. Corresponding value for Sweden is around 40% and CHP has still low share in the total power balance. Moreover, the electricity to heat ratio of the entire system is only 0.14 in 2011 [6]. Efficient use of existing DH demand for CHP generation is efficient energy utilization, which gives low CO_2 emissions.

Several studies have been done, which focus on the Swedish district heating. For instance, the potential for increased CHP generation in the Swedish DHS is studied in Knutsson et al. [15]. The well-established district heating in Sweden and the availability of biomass resources has also triggered other researches that focus on efficient use of biomass in district heating systems. Some studies along this line are: assessment and analysis of biomass gasification alternatives in district heating systems [16,17] and integrated production of heat, electricity and vehicle fuels in district heating systems [11,18].

Surplus of electricity and low electricity prices during the 1980s had been given as one of the many barriers for the slow development of CHP in the Swedish DHS. The situation is now different and the deregulation of the electricity market that took place in Europe and Scandinavia has now led to a common market for electricity in the area. For the Scandinavian countries, Nord Pool is the main marketplace for electricity. Some of the players in this market are also players in the German electricity market and there is a substantial exchange of electric power in northern Europe through both public and private power lines. This in turn has meant that electricity prices tend to become equal in the northern area. However, lack of transmission capacity and other regulations still imply different power prices in the region. There is a directive within the EU to establish a general market for electrical power throughout the EU [19]. Efforts are on-going to expand transmission capacity not only between the Scandinavian countries but also to the continent and within the member states. In the long term, this could mean that the whole of northern Europe will have a common electricity market with a common price. Since electricity price has a large influence on the competiveness of CHP,

The further development of the deregulated electricity market will play a key role on the future of DHS with CHP.

As mentioned earlier, DHS can play a significant role to achieve national and also international targets. This depends, however, on how existing and future heat demands are utilised. A proper system perspective, both from an economic and a climate point of view is needed. Besides, different technological solutions provide different power efficiency for the same heating demand.

The core motivation for this study is the following:

- District heating has large share in the total heat market of Sweden but the share of CHP is low. Is there a possibility to increase this share?
- The deregulation of the power market and the EU policy instruments. What is the impact on the competitiveness of DH CHP?
- The fossil fuel dominated power sector of Europe and the role of CHP in a local DHS to mitigate emissions.

With this in mind, this study examines a local DHS with regard to one main aspect: the implication of biomass and CO_2 emission costs on the choice of fuel and production technologies in DHS which today is characterised by high share of municipal waste in the fuel mix. All fuels are treated equally and different levels of CO_2 emission costs are considered as the main steering parameter. In this study, the local DHS is linked to the northern European power production system through calculated power prices resulting from different levels of emission costs. By using this case study, the paper seeks to answer some questions such as: What will the consequences be in terms of changes in energy carriers, overall system efficiency, environmental impact and costs? Is there a space for additional CHP under these conditions? Is the level of the current renewable incentive in the form of green electricity certificate high enough to encourage investment in low-carbon technology?

This paper is organised as follows. Section 2 gives a brief description of green electricity certificates and its impact on renewable target of Sweden. In Section 3, the model that is used in this study is briefly described. The studied system, the input parameters and simulated cases are presented in Section 4. Model simulations results and concluding discussions are presented in Sections 5 and 6.

2. Green electricity certificate

One of the energy and climate targets of the EU is to increase the share of renewable energy in the energy supply system. In the electricity sector, the target has been to increase the share of electricity generation from renewable sources. According to the directive from 2001, 22% of electricity within EU should come from such sources [20]. In order to meet this target, different measures are introduced in several countries across Europe. A response from Sweden was the introduction of green electricity certificate system (GECS) in 2003. The GECS covers since January 1, 2012, both Sweden and Norway. The goal of the joint certificate market is to increase the total annual renewable electricity production in Sweden and Norway with 26.4 TW h between 2012 and 2020. In short, GECS means that certificates are issued for each MW h electricity generated from renewable sources. To create a demand for these certificates, consumers are obliged to have a certain share of certificates corresponding to their power consumption. In this way, a market driven support mechanism is created with the aim to promote renewable energy based power generation. The main purpose of the joint certificate market is to utilise the renewable sources in both countries in efficient way. This will be possible, since the joint market is bigger than the individual market and investments can be made where it is suitable.

In the case of Sweden, power generation with certificate rights has increased continuously since the introduction of GECS. At the end of 2011, the total increase in generation was 19.8 TW h which is three times higher than the reference year 2002 [21]. However, the absolute increase is lower if only plants that are taken into operation after the introduction of GECS are taken into consideration. Although most of the generation are from plants existing prior to the introduction of the certificate system, biomass based power generation has the largest share in the Swedish certificate system. In general, the certificate system has played a significant role in achieving increased generation from renewable sources. A thorough study on the performance of Swedish GECS is given in [22].

The price of the certificate has a decisive role for future investments on renewables. The average spot price for electricity certificates in 2012 was 19 Euro/MW h and monthly average spot prices ranged from 16 to 24 Euro/MW h [23]. Future price development depends on factors such as electricity consumption, electricity prices, quota obligations and the supply of renewable electricity from eligible facilities. Another factor which may affect the price is reduced supply from eligible facilities. This can happen when old plants no longer receive certificate. This could raise the price of certificates. Certificates for 2013–2017 in December 2012 can be bought for 25–27 Euro/ MW h [24].

3. Method

In this study, the energy system optimisation method MODEST (Model for Optimisation of Dynamic Energy Systems with Time dependent components and boundary conditions) [25,26] based on linear programming [27] is used.

The MODEST model consists of an objective function and boundary conditions. The general formulation of the optimisation problem is expressed in the following form:

$$\text{Minimize}: \quad \sum_{j=1}^{n} c_j x_j \tag{1}$$

$$\text{Subject to} \sum_{j=1}^{n} a_{ij} x_j = b_i, \quad i = 1,\ 2,\ \ldots, m$$

$$x_j \geq 0 \quad j = 1,\ 2, \ldots, m \tag{2}$$

The objective function is expressed in Eq. (1). Some of the terms of the objective function are energy flows, energy costs, investment costs and fixed annual costs. Other terms included in this equation are, among other things, time division, discount rates, analysis periods and economic plant lifetimes. The boundary conditions (Eq. (2)) are mainly energy balance equations and different kinds of restrictions regarding availability of energy and power.

The objective function in the model is the system cost calculated as the net present value for a given period and given real interest rate. The criterion is to minimize the discounted system cost. With defined data and boundary conditions MODEST can suggest the most favourable combinations of present and potential equipment and energy flows.

MODEST has been used in many studies for optimisation/simulation of district heating and electricity generation. During the years, over 50 district heating systems and some national power supply systems have been studied using MODEST. The subject area of some of the studies include: collaboration between industry and district

heating utilities [28], absorption cooling based on district heating [29], integration of renewables [30] and poly-generation [11].

In this study, two simplified model consisting of a local DHS and the northern European power system are constructed using the above model. Northern Europe is represented in this case by Denmark, Finland, Norway, Sweden and Germany. When studying a single DHS, it is quite common to use historical market spot price data or other assumed data as a possible selling price for power production from existing/potential cogeneration units. In this study, shadow prices from the power system are used as an input to the DHS. When solving linear programming problems, valuable information can be obtained from the shadow prices. If applied on power production, a shadow price is the incremental cost of generating one extra MWh electricity. In a well-defined model with appropriate data, shadow prices can be helpful for power pricing. This is the main reason for considering northern European power system. In this way, the local DHS is linked indirectly to the power production system through the existing/potential cogeneration units. By doing so the choice of technology and utilisation of energy within the DHS system will be much more system optimal than running the model with assumed power price data.

4. Studied system and input data

4.1. General data

The considered system consists of the local DHS and the North European power system. Based on statistics from the ENTSO-E [31], Eurostat [32], Union of the Electricity Industry (EURELECTRIC) [31] and information from a local DH company, electricity production in the countries is identified. The total capacity and production in northern Europe based on type of energy source is shown in Table 1. As can be seen from the table, fossil fuels are the main source of generation followed by nuclear and hydro. The use of coal is very high, with a share of almost 70% of the total amount of fossil fuels. The major part of coal is used in condensing power plants. The use of natural gas for power production is growing. The newly built gas pipelines from Russia will probably increase the share of natural gas based power production in northern Europe, including Sweden. Wind power is increasing and has a high level of installed power but a low degree of utilisation. Wind has also the highest share among the renewable sources (excluding hydro). According to data from Eurostat, there was a total installed CHP capacity of 38 GW within the considered system. In terms of generation, the overall share of CHP in total generation was 13%. This is due to the rather low share in Germany and Sweden. The share of renewable in the fuel input to these CHP is highest in Sweden but generation capacity and production is lower compared to the rest of the countries. The total electricity consumption in the studied area was 968 TW h in 2010 and the corresponding net production was 974 TW h.

The local DHS has a district heating production of around 1700 GW h per year where waste and biomass are the predominant sources of energy, complemented by CHP from coal and oil and oil-fuelled heat-only boilers (HOB) Table 2.

4.2. Energy costs, new facilities and simulated cases

Fuel prices play a vital role in the local DHS's decision whether a certain technology is economically viable or not. It is hard to find accurate price information but for the sake of simplicity estimated costs are used. For wind power and nuclear power the annual operating cost is estimated and used as a fuel cost in the simulation model. Since the focus in this study is to assess the impact of different levels of biomass prices and emission allowances on the choice of fuels and production technologies, all other fuel costs are kept constant and they are assumed not to increase during the studied period more than the inflation rate. The cost of biomass and emission will be varied in such a way that it covers the interval from “low” to “high” levels. The level of cost and the amount of free allowance for emissions of CO_2 are under discussion within the European Union. In this study, no other taxes, fees or any kind of subsidy including green electricity certificate are considered in the simulations. Applied energy costs are listed in Table 3. It should be mentioned here that these prices are estimates and should by no means be considered indicative of actual prices.

Table 1
Installed power and power generation in northern Europe 2010 by type of production.

Type	Power (MW)	Energy (GW h)
Hydro	60 665	224 800
Nuclear	32 516	210 500
Fossil fuels	106 374	416 000
• **Coal**	57 394	280 000
• **Oil**	12 264	11 000
• **Gas**	36 716	125 000
Renewable	61 329	112 000
• **Wind**	33 796	51 000
• **Solar**	17 488	12 000
• **Biomass**	7 815	34 000
• **Waste**	2 230	15 000

Table 2
Fuel, boiler and power to heat ratio data for the local DHS.

Fuel	Output (MW)	Power/heat ratio
Waste	143	0.16–0.3
Biomass	68	0.22
Coal	83	0.27
Oil	350	0.33
Oil	250	

Table 3
Energy prices used in this study.

Fuel	Price (Euro/MW h)
Coal	12
Natural gas	32
Waste	5
Oil	35
Wind	9
Nuclear	5
Hydro	1

As this study examines the impact of biomass and CO_2 emission costs on the choice of fuels and technology, new facilities are also included as an option to existing plants. These are biomass based CHP, biomass integrated gasification combined cycle with CHP (BIGCC-CHP), natural gas combined cycle (NGCC) and NGCC-CHP. Data for the complementary technologies can be found in Table 4. Investment costs for new plants are estimates based on a report [33].

Based on the variations of the costs for biomass and emission allowances, some simulation cases are selected. The list of simulated cases is shown in Table 5.

5. Results

This section presents some of the results obtained from modelling and optimisation of the studied system subjected to different price variations. Two simplified models, one for a local

Table 4
Data for new power and CHP plants.

Type	Power/heat ratio	Investment cost Euro/kWe
Biomass CHP	0.4	3000
Coal power plant		1700
NGCC-CHP	1	1100
NGCC		800
BIGCC-CHP	0.7–0.8	3200
Wind		1800

Table 5
Simulated cases.

Case	Description
1	Emission allowance 5 Euro/t, biomass price variation 5–30 Euro/MW h
2	Emission allowance 10 Euro/t, biomass price variation 5–30 Euro/MW h
3	Emission allowance 20 Euro/t, biomass price variation 5–30 Euro/MW h
4	Emission allowance 30 Euro/t, biomass price variation 5–30 Euro/MW h

DHS and another for northern European power production system have been constructed.

As mention earlier, the main purpose of this paper is to study how the situation in the local DHS is affected by various biomass prices and the situation in the Northern European electricity market with different CO_2 costs. In general, the optimisation shows that existing CHP plants are used more or less in all simulated cases. Production from existing waste fired CHP is least sensitive to price variation except in few cases. This result is expected since waste has the lowest operational costs. On the other hand, the use of existing biomass-based CHP and coal-based CHP is more sensitive to changes in biomass and CO_2 costs. The remaining facilities are used in all calculation cases to cope with the heat demand during peak load. As far as new plants are concerned, biomass prices in the range of 5–10 Euro/MW h and emission costs in the range of 10–30 Euro/t encourage investment mainly in BIGCC-CHP and in some cases in traditional biomass CHP. The degree of utilisation of the new generation unit increases with increasing cost of emissions. In these cases, production from existing biomass and coal-based CHP plants decreases significantly. Investment in BIGCC-CHP plant will also improve the electricity-to-heat ratio of the studied DHS by up to 160%. Corresponding improvement obtained by the traditional biomass CHP is only 25%. Investment in new biomass-based generation is not viable when the price of biomass is higher than 10 Euro/MW h. In this case, the system tends to survive with existing production facilities. It is worth mentioning that low biomass prices alone would not make new investment in biomass-based generation units attractive. In other words, the CO_2 price level plays an important role for the competitiveness of the plant.

Based on applied natural gas price in this study, NGCC-CHP will not be selected in any of the simulated cases. However, a decrease in natural gas price in combination with biomass prices in the range of 20–30 Euro/MW h could make NGCC-CHP competitive. For instance, NGCC-CHP starts to enter the system when the initial price of natural gas decreases by 10% and the emission cost is 30 Euro/t.

Figs. 1–3 show results on fuel use, emission reduction and net income for all simulated cases. Even though BIGCC-CHP is the most optimal solution as far as new plants are concerned, the presented figures are based on biomass based production with current technology. Since no other taxes, fees or any kind of subsidy are considered in the simulated cases, the data shown in the figures may not represent actual operation.

Concerning the net emissions of CO_2, all simulated cases give a reduction in global emissions if locally generated power from existing and potential plants is assumed to replace power production based on coal (see Fig. 2). A combination of low biomass prices and high CO_2 emission costs gives maximum reduction. The reason for this is that at high electricity prices (due to high CO_2 emission costs), it is profitable to invest in large facilities that also partially replace existing less efficient cogeneration units.

The positive effect of low biomass prices and CO_2 emission costs is also seen in increased net income. In this case, the net income increases with increasing CO_2 emission costs (see Fig. 3). The revenue from electricity production plays a vital role on the

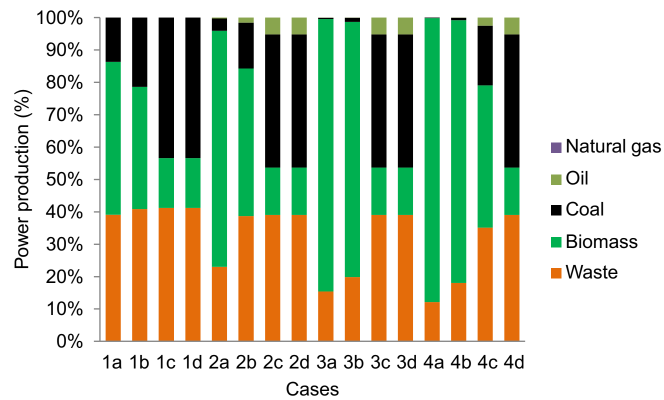

Fig. 1. Fuel share for power generation at different costs of biomass and emissions.

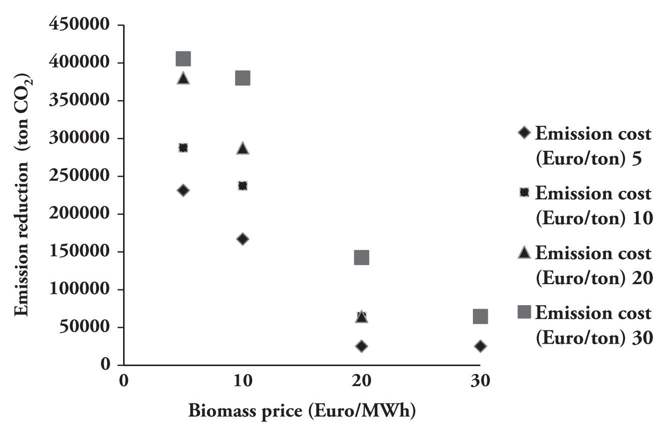

Fig. 2. Global emission reduction at different costs for biomass and emissions.

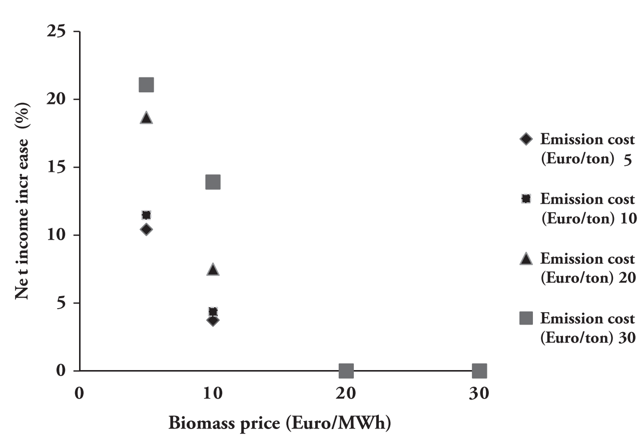

Fig. 3. Net income at different costs for biomass and emissions.

amount of the net income. High CO_2 emission costs give high electricity price and this encourages increased power generation. The BIGCC-CHP technology would give a higher net income than the traditional biomass CHP.

6. Concluding discussion

In this study, the impact of different levels of biomass prices and CO_2 emissions costs on the choice of fuels and production technologies is analysed. By indirect linking the local DHS with the north European power system, the study investigates the viability of the different technologies.

Based on the applied data, BIGCC-CHP is the best alternative technology that could utilise the heat demand efficiently by improving the electricity-to-heat ratio significantly. In some few cases, this alternative is also competitive with waste-based generation. However, this alternative or the conventional biomass technology option requires low biomass costs and emission costs in the range of 10–30 Euro/t. This shows that the currently established incentive method of green certificates may not be enough to make biomass the most economically viable option for the owner of a cogeneration plant. In order to obtain economic viability in investments in biomass based generation, the price level of the green certificate should be higher than the current value. As mentioned earlier, the average spot price of a green certificate in 2012 was around 20 Euro/MW h. This is equivalent to a reduction of biomass price by around 8 Euro/MW h. Based on the calculations, new biomass based power generation (either BIGCC-CHP or biomass CHP) is selected when the price of biomass is in the range of 5–10 Euro/MW h. The market price of biomass, however, is higher than this. For instance, the average price of biomass (wood chips) in Sweden was higher than 20 Euro/MW h in 2010 [34]. This implies that the market price of a green certificate should be higher than the current level in the long term. Moreover, the solution of biomass based production put a demand on higher costs for CO_2 emissions. In this case, emissions costs in the range of at least 10 Euro/t are needed.

Shwaiger et al. [35] developed a model and analysed the competitiveness of biomass-based power generation compared to coal-based generation under EU-ETS. The model was also applied on some other EU countries, including Sweden. Although the applied price of biomass in Sweden is not known, the study suggests that the cost of CO_2 needs to be at least 15 Euro/t for biomass CHP to be competitive with coal. This is also to some extent comparable with the price level indicated in this study. Up to now, the price for CO_2 emissions has not been high enough to reach the level required in this study. If this situation prevails then the competitiveness of low carbon technologies would be vulnerable.

Increasing costs for CO_2 emissions and thereby a higher market price for power stimulates technologies with high power efficiency. In this way, the heat demand can be utilised efficiently. The greater amount of power that can be produced based on the district heat demand the higher the reduction of global CO_2 that can be achieved. From the broader system perspective, facilities with high electrical efficiency makes the most out of the given heat demand. This makes BIGCC-CHP a better solution than the traditional biomass based CHP. However, this technology is still not available commercially. Thus, the choice will have to be biomass based CHP with current technology. It is worth mentioning that NGCC-CHP, due to its high electrical efficiency, can be attractive solution both from economic and environmental point of view but this will require lower gas prices and a combination of higher biomass prices and CO_2 emissions costs.

It's also obvious that an increasing cost for CO_2 emissions is a much stronger steering parameter than a direct or indirect subsidy of biomass cost. However, the CO_2 price development so far may not confirm this statement. Since the beginning of the third phase of the EU ETS, the price of CO_2 has not been higher than 5 Euro/t [36]. At this level, it would be quite difficult to promote investment in biomass-based production technology. It is therefore important that policymakers should aware of the consequence of such a development. This situation can lead to reduced investment in green technology and affect the energy and climate goal. This shows that there might be a need for further action at national and international level in order to create stability and continuity in this direction.

Biomass is used intensively in Sweden and a significant amount is used in the forestry industry and the heating sector. Although the share of biomass (in this case including peat and combustible waste) in the national energy supply is significantly high, the well-established district heating system could possibly be utilised efficiently if power generation units with high electricity efficiency are deployed. Hence, the use of any fuel in district heating system should be seen from broader system perspectives with the aim of optimal utilisation of existing and future heat sink and what it means in terms of reduction of global CO_2.

The results presented in this study are based on a simplified model study where several data are assumed values. It is not the purpose of this study to draw certain conclusions in favour of a certain technology or a certain fuel. Since the results obtained are highly dependent on the applied data and assumptions, they should be viewed with great caution.

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References

[1] Official Journal of the European Union, (2009). Decision adopted jointly by the European Parliament and the Council, Decision No 406/2009/EC of the European Parliament and of the Council—On the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020.
[2] EC (European Commission). Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources COM (2008) 19 final, Brussels, Belgium; 2008.
[3] EC (European Commission). Second Action Plan for Energy Efficiency: Realising the Potential COM (2006) 545 final, Brussels. Belgium; 2006.
[4] EC (European Commission). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.
[5] Behnaz Rezaie, Rosen Marc A. District heating and cooling: review of technology and potential enhancements. Appl Energy 2012;93:2–10.
[6] Swedish District heating Association. 〈http://www.svenskfjarrvarme.se/〉.
[7] Nilsson SF, Reihav C, Lygnerud K, Werner S. Sparse district-heating in Sweden. Appl Energy 85(2008) 555–564.
[8] Reihav C, Werner S. Profitability of sparse district heating. Appl Energy 2008;85:867–77.
[9] Amiri S, Moshfegh B. Possibilities and consequences of deregulation of the European electricity market for connection of heat sparse areas to district heating systems. Appl Energy 2010;87:2401–10.
[10] Difs K, Danestig M, Trygg L. Increased use of district heating in industrial processes: impact on heat load duration. Appl Energy 2009;86:2327–34.
[11] Ilic Danica Djuric, Dotzauer Erik, Trygg Louise. District heating and ethanol production through polygeneration in Stockholm. Appl Energy 2012;91:214–21.
[12] Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings, 〈http://eur-lex.europa.eu〉.
[13] Münster Marie, Erik Morthorst Poul, Larsen Helge V, Bregnbæk Lars, Werling Jesper, Henrik Lindboe Hans, et al. The role of district heating in the future Danish energy system. Energy 2012;48:47–55.
[14] Eurostat, (2011), Energy transport and environment indicators, Luxemburg, Publications Office of European Union, Edition 2011.

[15] Knutsson D, Werner S, Ahlgren EO. Combined heat and power in the Swedish district heating sector—impact of green certificates and CO_2 trading on new investments. Energy Policy 2006;34(18):3942–52.

[16] Fahlén E, Ahlgren EO. Assessment of integration of different biomass gasification alternatives in a district-heating system. Energy 2009;34(12):2184–95.

[17] Börjesson M, Ahlgren EO. Biomass gasification in cost-optimized district heating systems—a regional modelling analysis. Energy Policy 2010;38(1):168–80.

[18] Truong NL, Gustavsson L. Integrated biomass-based production of district heat, electricity, motor fuels and pellets of different scales. Appl Energy 2009;34 (12):2184–95.

[19] EC (European Commission). Amending Directive 2003/54/EC concerning common rules for the internal market in electricity. COM (2007) 528 final, Brussels, Belgium; 2007.

[20] The European Parliament and the Council of the European Union, 2001. Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy in the internal electricity market. Brussels, Belgium.

[21] Swedish Energy Agency, 2009. Elcertifikatsystemet 2012, ET2012: 30, Swedish Energy Agency, Eskilstuna.

[22] Bergek Anna, Jacobsson Staffan. Are tradable green certificates a cost efficient policy driving technical change or a rent-generating machine? Lessons from Sweden 2003–2008 Energy Policy 2010;38(2010):1255–71.

[23] Svensk Kraftmäkling (SKM). 〈http://www.skm.se/〉.

[24] Henning D. MODEST-An Energy System Optimisation Model applicable to local utilities and countries. Energy Int J 1997;22(12):1135–50.

[25] Gebremedhin A. Regional and industrial co-operation in district heating systems LIU. Dissertation No. 849 Linköping Institute of Technology, SE-581 83 Linköping, Sweden.

[26] Bazaraa MS, Jarvis JJ, Sherali HD. Linear programming and network flows. New York: Wiley; 1990New York: Wiley; 1990 (NY, U.S.A).

[27] Karlsson M, Gebremedhin A, Klugman S, Henning D, Moshfegh B. Regional energy system optimization—potential for a regional heat market. Appl Energy 2009;86:441–51.

[28] Trygg Louise, Amiri Shahnaz. European perspective on absorption cooling in a combined heat and power system: a case study of energy utility and industries in Sweden. Appl Energy 2007;84(12):1319–37.

[29] Gebremedhin A, Karlsson B, Björnfot K. Sustainable energy system—a case study from Chile. Renewable Energy 2009;34:1241–4.

[30] Statistical Yearbook 2011, European Network of Transmission System Operators for Electricity, Secretariat of ENTSO-E, Avenue de Cortenbergh 100, B-1000 Brussels.

[31] Eurostat, Electricity production and supply statistics 2011, available at 〈http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/〉.

[32] EURELECTRIC Power Statistics 2012, available at 〈http://www.eurelectric.org/〉.

[33] Electricity from new and future plants 2011. Elforsk AB, Stockholm.

[34] Statistics Sweden, SCB 2013; Energy and transport statistics, Wood fuel-and peat prices, N0. 1/2013, Örebro, Sweden.

[35] Schwaiger Hannes, Tuerk Andreas, Pena Naomi, Sijm Jos, Arrasto Antti, Kettner Claudia. The future European Emission Trading Scheme and its impact on biomass use. Biomass Bioenergy 2012;38(2012):102–8.

[36] European Energy Exchange (EEX). 〈http://www.eex.com/〉.